Extending the Range of Fuel Consumption Modeling and Emission Factor Development to Natural Fuel Types in The Blue Mountain...

Extending the Range of Fuel Consumption Modeling and Emission Factor Development to Natural Fuel Types in the Blue Mountain Forested Regions of Eastern Oregon

98-2-442

by

Roger D. Ottmar and Darold E. Ward

Final Report - February, 1996

EPA/IAG Identification No. DW12957138-01-0 (PNW-94-0514)

Title: Fuel Consumption and Emissions of Air Pollutants from Prescribed Underburns of Eastern Oregon and Washington

Submitted to: **U.S. Environmental Protection Agency, EPA Region X, Seattle, WA**

Submitted by: **U.S. Department of Agriculture, Forest Service**
Fire and Environmental Research Applications Group
Pacific Northwest Research Station, Seattle, WA

Addresses of Principal Investigators:

Roger Ottmar
Seattle Forestry Sciences Laboratory
Pacific Northwest Research Station
4043 Roosevelt Way NE
Seattle, Washington 98105
Phone (206) 553-7815, Fax 553-7709

Darold Ward
Fire Sciences Laboratory
Intermountain Research Station
P.O. Box 8089
Missoula, MT 59807
Phone (406) 329-4862, Fax 329-4863

Abstract

Fuel loading and fuel consumption were measured on four prescribed burns with a natural fuel component. These sites were in the Blue Mountains of northeastern Oregon. Emissions were characterized on three of these sites.

The fuel consumption was typical of a moderately wet spring burn. Total fuel consumed ranged from 7.1 tons per acre on Three Troughs #4 to 14.2 tons per acre on Three Troughs #2. Nearly 100 percent of the 0 to 1 inch diameter fuels were consumed while only 40 to 70 percent of the 1 to 3 inch fuels were consumed (0.2 to 1.7 tons per acre). Large fuel diameter reduction ranged from 0.69 to 3.0 inches and amounted to 1.0 to 1.9 tons per acre. Average litter reduction ranged from 0.56 to 1.05 inches which amounted to 1.7 to 3.2 tons per acre. Duff reduction ranged from 0.14 to 0.53 inches which amounted to 1.7 to 6.4 tons per acre.

A fuel consumption software program called CONSUME, adequately predicted the fuel consumption of the small and large fuels, but under-predicted the fuel consumption of the forest floor. The internal equations of CONSUME were designed from data collected at clearcut prescribed fires and will need to be further tested and possibly modified to better represent the combustion process for natural fuels. FOFEM, another fuel consumption software developed for the Intermountain region predicted the fuel consumption of the small fuels well but substantially under-predicted the consumption of the larger fuels and over-predicted the consumption of the forest floor.

The emission factors for CO, CH_4, NMHC, and PM2.5 for the eastern Oregon underburns are comparable to those of logging slash fires in the Pacific Northwest (Ward and Hardy, 1991). When the weighted average combustion efficiency of 0.882 in Ward and Hardy's (1991) equations is used, calculated emission factors are 93.1, 4.6, 3.6, and 8.5 g kg^{-1}, respectively, for CO, CH_4, NMHC, and PM2.5. The values are -10, +0.5, +8, and -67% of those measured for the underburning experiments, suggesting that the emissions of smoke particles may be underestimated by previous models of Ward and Hardy (1991).

These data from the Three Troughs units are being added to a much larger data set composed of prescribed fire fuel consumption information collected from ponderosa pine and mixed conifer natural fuel burns across the western states. This database is currently being used to modify the fuel consumption models for implementation into a new version of CONSUME, scheduled for release in 1996. The equations will also be added to a new version of the Emissions Production Model, scheduled for release in 1997. The Three Troughs units are valuable additions to this data set.

Table of Contents

List of Figures

Page

List of Tables

Introduction

Fire is the single most important ecological disturbance process throughout the Blue Mountain Region (Mutch and others 1993, Agee 1993). It is also a natural process that maintains a diverse and rich ecological landscape. Fire suppression and timber harvesting have drastically altered this process during the past 50 to 90 years. Scientists, managers, and the public agree that as a result of human intervention and long term climatic change, the ecological system of the Blue Mountains is less healthy, less diverse, and more susceptible to larger and more destructive wildfires than in the past. Analysis of current and historical aerial photographs for the Forest Health Assessment (Huff and others 1995) in eastern Oregon and Washington bears this out. This same analysis indicates there has been an increase in fuel loading, crown fire potential, and smoke production potential since the historical period brought on by selective logging and fire suppression activities.

Prescribed fire, often in combination with other management techniques, can be used to restore ecosystems to a more desirable ecological state while simultaneously reducing the potential for catastrophic wildfires. Unfortunately, prescribed fire runs contrary to current federal and state environmental laws because any fire has the potential to degrade ambient air quality, impair visibility, and expose the public to unhealthy pollutants.

For areas in the United States where prescribed fire is widely practiced, data on fuel consumption, emission factors, and source strength were collected for forest fuel types generated from logging activity. Much of this data has been incorporated into models used in smoke management guidelines (Southern Forest Fire Laboratory 1976, NWCG 1985), and smoke management inventories such as the one presented by Ward and others in 1994. Recently, there has been a shift in prescribed burning emphasis and a majority of the prescribed burning is occurring in naturally created fuels. Little research has been done to characterize the fuel consumption and emissions from prescribed fires in these fuel types. This report presents fuel

consumption and emission characterization from 4 prescribed burns in natural fuels on the Hepner Ranger District in the Blue Mountains.

Background

Fuel Consumption

Predicting the consumption of woody fuel and forest floor biomass during prescribed fires is essential to the successful application of fire onto the landscape. It is the critical variable driving smoke production and the possible degrading impacts on air quality. Consumption of small woody fuel (3-inch diameter and smaller) is strongly influenced by preburn loading (Norum 1977, Martin and others 1979, Brown and others 1985). Consumption of the larger woody fuels (greater than 3- inches in diameter) depends primarily on moisture content (Norum 1977, Sandberg and Ottmar 1985, Brown and others 1991, Ottmar and others 1993).

Empirical relationships have been derived for duff consumption throughout the western United States. Sandberg (1980), Little and others (1985), and Ottmar and others (1993) developed models for clearcut and partial cut prescribed fires in the Douglas-fir and western hemlock types of western Washington and Oregon and found that large fuel consumption, duff moisture content, and large fuel moisture content were the key variables. Brown and others (1985) compiled duff consumption data from prescribed fires in partial cuts, clearcuts, and undisturbed stands from the northern Rockies and found preburn duff depth and duff moisture content drive the consumption. Harrington (1987) reported on 10 prescribed burns in Arizona ponderosa pine sites and also found duff moisture content and preburn duff depth controlled the duff consumption. Except for research by Brown and others (1985) and Harrington (1987), most emphasis has been directed toward prescribed fires in areas where humans have influenced the fuel composition through logging.

The Fire and Environmental Research Applications Group of the Pacific Northwest Research Station has been a leader in the development of prescribed fire and fuel consumption models (Ottmar and others 1993). Through this effort, we have a wealth of fuel consumption predictive algorithms for various fuel bed components and combustion phases for prescribed burning in Douglas fir/hemlock, west coast hardwoods, and associated species of logging slash. In addition, ongoing fuel consumption research by the Pacific Northwest Research Station has been directed toward natural fuel prescribed burning of the spruce types in Alaska, ponderosa pine types of the southwest, and mixed conifer regions in eastern Oregon and Washington. However, this research has been limited and a much larger effort needs to be directed towards natural fuels prescribed burning.

Emissions

The Intermountain Research Station, Fire Chemistry Research Work Unit, has the principal responsibility nationally for developing emissions characteristics and models for the release of smoke from fires in wildland fuel types. For the western states of Washington, Oregon, and California, Ward and Hardy (1991) studied the emissions from prescribed fires in logging slash. These prescribed fire studies covered a range of fuel types including:

1. Douglas fir/hemlock forests in western Washington and Oregon,
2. Pacific Coast hardwoods (alder, vine maple, etc.) In western Washington and Oregon,
3. ponderosa pine/lodgepole forests in eastern Washington and Oregon,
4. other mixed conifer broadcast burns on the east side of the Cascade mountains,
5. piled slash of conifers west of the Cascade mountains, and
6. chaparral in California.

These data were used to develop emission factor models for primary pollutants as a function of combustion efficiency.

The fuel consumption and emissions characterization of these natural fuels will improve our modeling capability and further our ability to:

1. develop a tradeoff analysis of total smoke, rate of smoke production, duration of smoke production, etc., for natural fuel prescribed burns and wildfires;

2. evaluate the difference in fuel consumption, total emissions production and duration of emissions production from natural fuel prescribed fires (similar to low- intensity wildfire) in comparison to fires that are prescribed to reduce fuels from logging activities;

3. determine source contributions of smoke from prescribed burning at receptor sites;

4. provide a basis for the fair allocation of emissions released;

5. develop an improved source strength/heat release model for invoking dispersion models;

6. provide information on characteristics of particles that would enhance an evaluation of the effects of particles from slash burning on visibility reduction; and

7. assess the production of gases and particles important to global warming.

Objectives

The objectives of this project were to measure the fuel consumption and emissions from a minimum of three natural fuel prescribed fires in the Blue Mountains of northeastern Oregon. Specific objectives were:

1. to deploy air sampling systems that could survive a fire environment;

2. to make multiple real time measurements of the major combustion gases including CO_2 and CO within several meters of the tops of the flames. These gases will be measured continuously over the life of the fire from ignition to extinction of the smoldering combustion phase;

3. to collect separate samples of particles (less than 2.5 micrometers in diameter) of the flaming and smoldering combustion phases for the analysis of organic, graphitic, and inorganic components;

4. to collect integrated samples of the gases of each combustion phase for subsequent analysis to profile the trace organic compounds and selected other compounds that may be important in global climate change scenarios;

5. to obtain vertical and horizontal airflow vector data for computing the flux of emissions and carbon from the site over the duration of the fire;

6. to characterize the preburn loading of all fuel components including small and large woody fuels, and forest floor material using standard inventory techniques;

7. to measure the consumption of all fuel components;

8. to compare measured fuel consumption with predicted results from CONSUME (Ottmar and others 1993) and FOFEM (Keene and others 1994); and

9. to input biomass consumption measurements into a larger data base to be used for modification of fuel consumption models for natural fuels.

Study Area

The Three Troughs Study Area was located on the Hepner Ranger District in the Blue Mountains of northeast Oregon (figure 1). The area contained large diameter ponderosa pine with a minor understory of Douglas-fir and white fir. The slope was flat. Limited logging had occurred in the area over 40 years ago. A prescribed burn was scheduled for the area to maintain the park-like structure and reduce the competition from natural regeneration. Four study sites within this area were selected.

Procedures

The research was coordinated closely between the Hepner Ranger District, Pacific Northwest Research Station's Fire and Environmental Resource Applications Group, and Intermountain Fire Sciences Laboratory Air Chemistry Project. The Hepner Ranger District personnel designed the prescribed burn plan and conducted the burn. The Pacific Northwest Research Station located the study area and study sites, inventoried the fuels before and after the prescribed burn, coordinated the burning activity, and analyzed the biomass loading and consumption data. The Intermountain Fire Science Laboratory performed all emissions characterization work including collecting and analyzing the data from each burn.

Plot Layout

Four study sites were selected within the Three Troughs Study Area and named Three Troughs #1, #2, #3, and #4. Fuels were inventoried on all four sites. Emissions were characterized on three sites (Three Troughs #1, #2, and #3). Each study site was approximately 5 acres in size with a uniform fuel bed, slope, and aspect. Eighteen permanent plots were established in a systematic grid to cover the entire site (figure 2). One permanent and 3 to 4 semi-permanent 50-foot transect lines were randomly directed from each plot for woody fuel measurements. This design resulted in 80 transect lines per site, totaling 4000 feet in length.

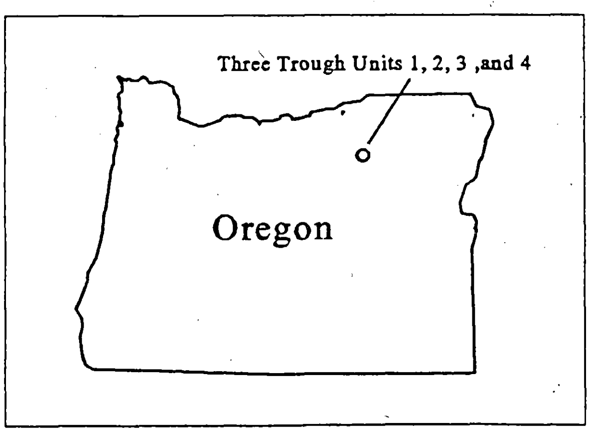

Figure 1. Location of Three Troughs prescribed burn units.

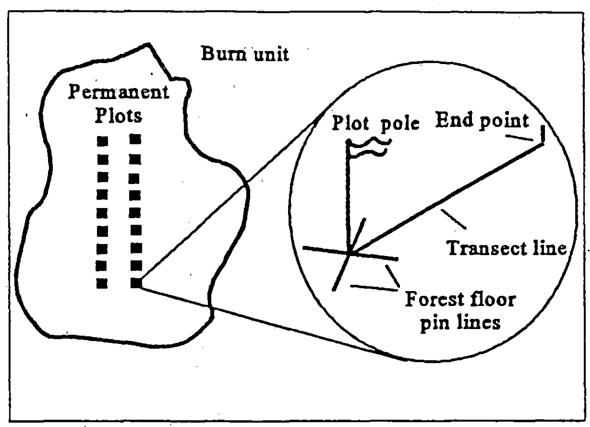

Figure 2. Permanent plot layout.

Preburn Fuels Inventory

The 0 to 0.25 inch and 0.25 to 1.0 inch diameter woody fuels were tallied along the first 3.3 feet and 6.6 feet of each permanent transect line according to Brown (1974). The 1 to 3 inch diameter woody fuels were tallied along the entire length of each transect line. Diameter measurements were recorded for each woody log greater than 3 inches in diameter intersected by the 80 transect lines radiating from the center points. The species and soundness was also noted. Diameter measurements were used to calculate the mass of the large woody fuels using formulas developed by Brown (1974) and wood densities found in the USDA Wood Handbook (1985). Sixteen litter and duff depth measurements were collected around each plot using metal pins (see section on fuel consumption).

Fuel Consumption

The 0 to 0.25, 0.25 to 1, and 1 to 3 inch diameter woody materials were tallied along the permanent transect lines following the burn to determine fuel consumption. Consumption of large fuels was measured as diameter reduction (which was converted to volume reduction) from 20 to 40 randomly chosen logs, 3 to 9 inches in diameter. The logs intersected fuel-inventory transect lines established at each of 18 permanent center plots. A fuel moisture sample was obtained from both the large and small end of each log immediately before the burn. Wires with numbered tags (for later identification) were tightly wrapped around each log before burning and were cinched up after burning; the exposed wire lengths were then measured to determine diameter reduction.

Litter and duff consumption were measured as depth reduction according to procedures adapted from Beaufait and others (1977). Sixteen metal pins were inserted flush with the litter layer around each permanent plot. Duff reduction was determined in the field by measuring the exposed length of the metal pin following the fire and subtracting the litter depth.

Figure 3. Wiring log to measure fuel consumption.

Total duff was determined by measuring the distance between the top of the pin (minus the litter layer) and the mineral soil. A total of 288 metal pins were placed at each site. Duff included the fermentation layer and humus layer.

Other Independent Variables

Average woody fuel moisture content was determined from two samples collected from each of the 20 wired logs just before the burn. In addition, 15 fuel moisture samples from the 0.25 to 1.0 and 1.0 to 3.0 inch diameter woody fuels were collected. All woody samples were oven-dried at 100 degrees centigrade for 48 hours.

Average duff-moisture content for each unit was calculated from 36 moisture samples. The samples were collected near each duff-consumption plot. If a distinct dry layer was found in the duff profile, samples from both the wet and dry layers were collected and the dry-layer depth was recorded. All samples were oven dried at 100 degrees centigrade for 48 hours.

The nearest representative weather station was used to monitor environmental conditions before burning each unit. A belt weather kit was used to collect on-site weather variables of relative humidity, temperature, and wind speed every 15 minutes during the burn.

Emissions Characterization

The emissions were characterized on Three Troughs #1, #2, and #3 with the use of the Fire Atmosphere Sampling System (FASS) packages (figure 4). The FASS packages were specially designed for withstanding the harsh thermal environments of prescribed fires and have been used on prescribed fires in different locations including Ontario (1989, 1990, 1991), British Columbia (1991, 1993, 1994), North Carolina (1990), Wyoming (1991), eastern Oregon (1991, 1994), Brazil (1990, 1991, 1992, 1993, 1994), South Africa (1991, 1992), and Zambia (1992, 1993, 1994).

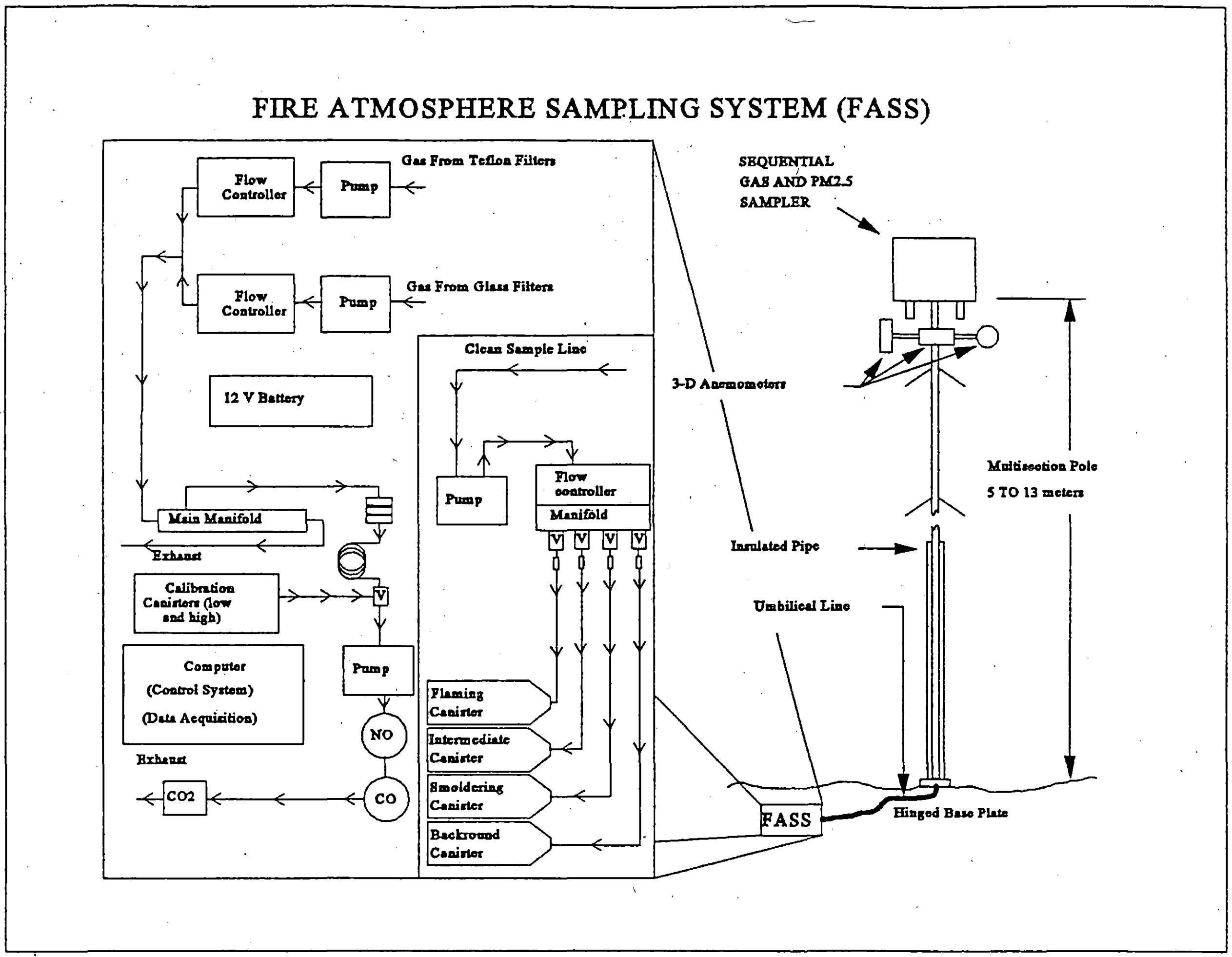

Figure 4. Design of Fire Atmosphere Sampling System.

The FASS packages are used to collect both continuous emissions and fire dynamics data and to collect grab samples of emissions of gases and particulate matter. The system was designed for sampling emissions from area burns, pile burns, and backing and heading fires. From the data collected with each package, the concentrations of CO and CO_2 are measured once each second. Vector wind direction, speed, and temperature at several locations are measured each second or at a longer specified interval. Grab samples of the particles less than 2.5 μm diameter (PM2.5) are collected on both glass fiber and Teflon filter mats for analysis of the PM2.5 concentration as well as the content of carbon and trace elements of the fine particles. Gas samples are collected in canisters coincident with the PM2.5. The canister samples are analyzed for trace gas concentrations of several "greenhouse" gases. A Quality Assurance Plan is available. This Plan was prepared for work done through funding provided by the U.S. Environmental Protection

Agency (EPA). The Plan was approved by the EPA and provides the protocols used for standards, sample integrity, and other quality assurance activities.

Figure 5. FASS tower.

The data were used to compute emission factors by phase of combustion, combustion efficiency (η), rate of release of carbon on a unit area basis, rate of consumption of biomass (kg $^{-2}$ s^{-1}), and rate of heat release (kW m^{-2}). The ratio of consumption of fuels by phase of combustion was also determined from this data. The rate of consumption is integrated, and the total consumption will be compared with, the inventoried measurements made on the ground.

The computerized data acquisition and sampling protocol system onboard each FASS package allows sampling protocols to be tailored to the specific fire and weather conditions. The computer system also provides for calibration of the CO and CO_2 sensors during the period of sampling. In addition, the computer modulates the sampling protocol and the system of FASS packages can be interconnected for simultaneous sampling or each triggered independently. Each FASS package monitors the background conditions prior to the arrival of the fire and detects the presence of the fire which initiates the start of the sampling protocol. Both pre- and post-fire calibration protocols are followed for quality control assurance.

<u>Results</u>

The Three Troughs sites #1, #2, #3, and #4 were ignited by hand held drip torches on May 8 and 9, 1994. A combination of strip head fires and backing fires were used to light most of the units. The weather conditions and fuel moisture contents were within the ranges indicated by the prescribed burn plan and the objectives were met.

Fuel Loading

Small and large fuel loadings were light. Loading of the small fuels (0 to 3 inch in diameter) ranged from 1.1 tons per acre on Three Troughs #1 to 4.1 tons per acre on Three Troughs #2. Large woody fuel loading ranged from 2.8 tons per acre on Three Troughs #1 to 15.2 tons per acre on Three Troughs # 4. Litter and duff depths were typical for these types of stands, with total forest floor depths (litter plus duff) ranging from 2.14 inches on Three Troughs # 1 to 3.08 inches on Three Troughs #3 (table 1).

Weather

No extreme weather conditions were noted during the study burns. Relative humidity during the burns ranged from 40 to 50 percent; temperature ranged from 55 to 70 degrees and wind speed ranged from 5 to 12 miles per hour, generally from the south.

Fuel Moisture Content

The burns occurred early in the spring and the fuel moisture contents were high. The 0.25 to 1 inch diameter fuels ranged from 13 to 20 percent moisture while the 1.0 to 3.0 inch diameter fuels ranged from 22 to 30 percent (table 1). The large fuels (3+ inches) were very wet and ranged from 42 to 75 percent moisture. The duff was considered moderately wet in Three Troughs #4, averaging 112 percent, while Three Troughs #1 averaged 59 percent. The litter layer for all units was relatively dry and moisture ranged from 11 to 20 percent.

Fuel Consumption

Total fuel consumed ranged from 7.1 tons per acre on Three Troughs #4 to 14.2 tons per acre on Three Troughs #2 (table 2). Nearly 100 percent of the 0 to 1 inch diameter fuels were consumed while only 40 to 70 percent of the 1 to 3 inch fuels were consumed (0.2 to 1.7 tons per acre). Large fuel diameter reduction ranged from 0.69 to 3.0 inches and amounted to 1.0 to 1.9 tons per acre. Average litter reduction ranged from 0.56 to 1.05 inches which amounted to 1.7 to 3.2 tons per acre. Duff reduction ranged from 0.14 to 0.53 inches which amounted to 1.7 to 6.4 tons per acre. All fuel consumption data is presented in Table 2.

Table 1. Preburn fuel loading and fuel moisture content.

Unit Name	Preburn Fuel Loading 0 - 1/4"	1/4 - 1"	1 - 3"	3+"	Total Woody	Litter	Duff	Total Forest Floor	Total Fuels	Forest Floor Litter Depth	Duff Depth	Fuel Moisture Content 1/4 - 1"	1 - 3"	3+"	Litter	Upper Duff	Lower Duff
	(Tons/Acre)									(Inches)		(Percent)					
Three Troughs 1	0.2	0.4	0.5	2.8	3.9	3	13.7	16.7	20.6	1	1.14	20	23	42	18	---	59
Three Troughs 2	0.6	1.1	2.4	10.0	14.1	3.9	16.5	20.4	34.5	1.31	1.36	18	22	75	11	---	75
Three Troughs 3	0.3	0.5	1.1	4.8	6.7	4.9	16.3	21.2	27.9	1.63	1.35	13	30	67	20	44	97
Three Troughs 4	0.3	0.5	1.6	15.2	17.6	3.7	11.4	15.1	32.7	1.26	0.95	13	26	73	19	---	112

Table 2. Total fuel consumption

Unit Name	0 - 1/4"	1/4 - 1"	1 - 3"	3+"	Total Woody	Litter	Duff	Total Forest Floor	Total Fuels	3+" Diam. Reduction	Litter Reduction	Duff Reduction
	(Tons/Acre)									(Inches)		
Three Troughs 1	0.2	0.2	0.2	1.2	1.8	1.7	3.8	5.5	7.3	3	0.56	0.31
Three Troughs 2	0.6	1	1.7	1.9	5.2	2.7	6.3	9	14.2	0.69	0.91	0.52
Three Troughs 3	0.3	0.4	0.6	1.0	2.3	3.2	6.4	9.6	11.9	0.81	1.05	0.53
Three Troughs 4	0.3	0.4	0.6	1.9	3.2	2.2	1.7	3.9	7.1	0.75	0.74	0.14

The fuel consumption by combustion stage was not measured directly. The flaming and smoldering stages were modeled using equations developed by Ottmar (1983). Woody fuel flaming consumption ranged from 0.4 to 1.8 tons per acre (tables 3 and 4 and figure 6). A greater mass of woody fuels was consumed during the smoldering stage and ranged from 1.4 to 3.4 tons per acre. Because of the high fuel moisture conditions, a majority of the biomass consumed during the flaming stage was in the 0 to 1 inch diameter size class with the larger fuels contributing to the smoldering stage. The flaming forest floor consumption ranged from 3.3 to 4.5 tons per acre while the smoldering consumption ranged from 0.6 to 5.2. Generally, the litter layer was consumed during the flaming stage and the duff layer was consumed during the smoldering stage (tables 3 and 4) .

Table 3. Flaming fuel consumption.

Unit Name	0 - 1/4"	1/4 - 1"	1 - 3"	3+"	Total Woody	Litter	Duff	Total Forest Floor	Total Fuels
	(Tons/Acre)								
Three Troughs 1	0.2	0.2	0	0	0.4	1.7	2.3	4	4.4
Three Troughs 2	0.6	1	0	0.2	1.8	2.7	1.8	4.5	6.3
Three Troughs 3	0.3	0.4	0	0	0.7	3.2	1.2	4.4	5.1
Three Troughs 4	0.3	0.4	0	0	0.7	2.2	1.1	3.3	4

Table 4. Smoldering fuel consumption.

Unit Name	0 - 1/4"	1/4 - 1"	1 - 3"	3+"	Total Woody	Litter	Duff	Total Forest Floor	Total Fuels
	(Tons/Acre)								
Three Troughs 1	0.0	0.0	0.2	1.2	1.4	0	1.5	1.5	2.9
Three Troughs 2	0	0	1.7	1.7	3.4	0	4.5	4.5	7.9
Three Troughs 3	0	0	0.6	1	1.6	0	5.2	5.2	6.8
Three Troughs 4	0	0	0.6	1.9	2.5	0	0.6	0.6	3.1

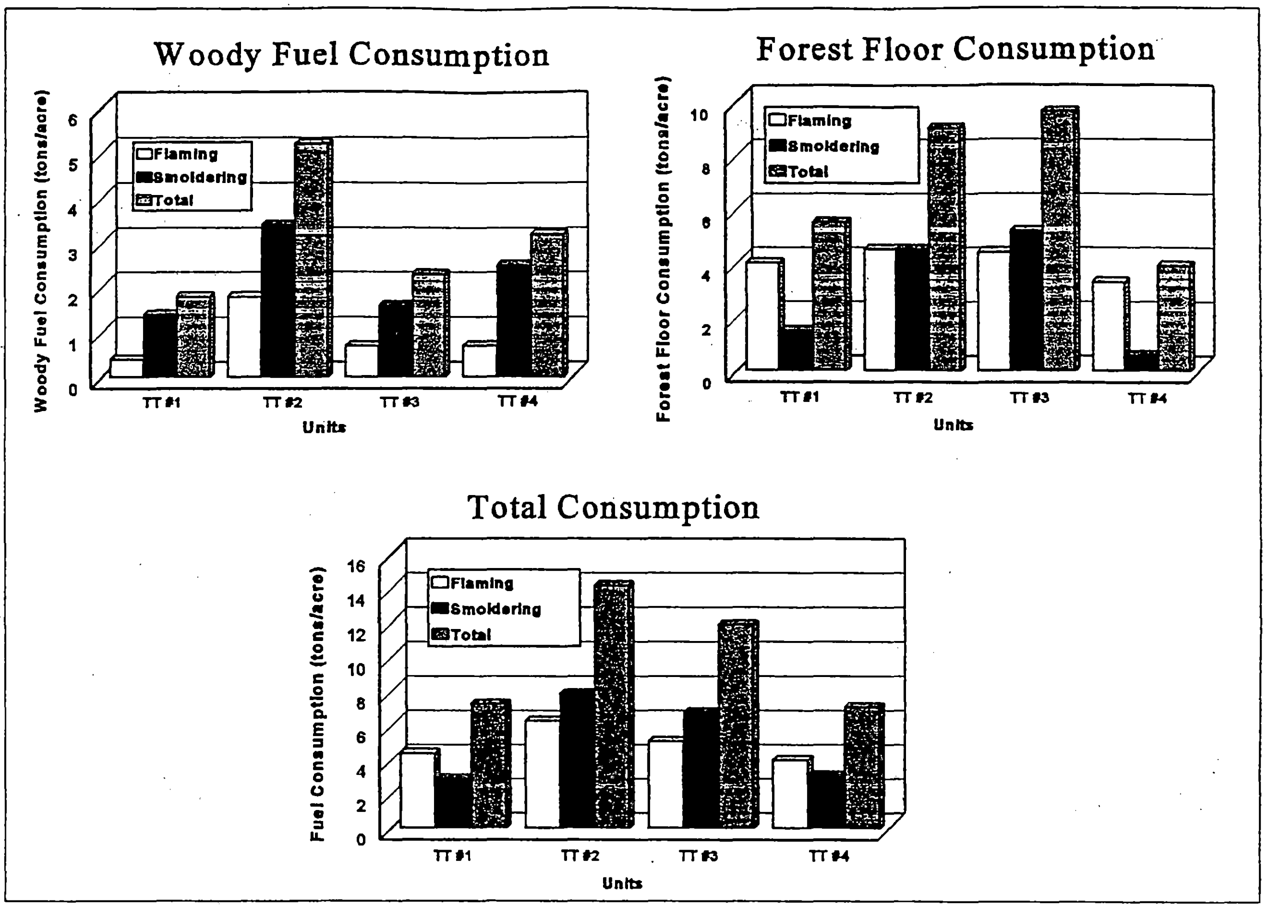

Figure 6. Fuel consumption by combustion phase.

The limited data set did not allow a comprehensive regression analysis to develop new and more robust fuel consumption equations for natural fuels in the ponderosa pine fuel type. However, a limited linear regression analysis was performed which will give us insight into factors controlling fuel consumption in natural fuel types. These data will also be compiled into a much larger data set (acquired during 1993 and 1994) and used to modify consumption equations currently in existence.

Consumption levels of woody fuel and duff were regressed against several independent variables. The 0 to 3 inch diameter woody fuel consumption was best correlated with the preburn fuel loading of the same size class (figure 7). This is consistent with other research (Brown and others 1991, Ottmar and others 1993). No relationship was found between small fuel consumption and small fuel moisture content. The large fuel consumption data set range was limited. This made any regression attempt invalid.

The duff reduction was most strongly correlated with preburn duff depth. Again, this was consistent with previous work (Brown and others 1991) but not consistent with Ottmar and others (1993) who found duff consumption to be well correlated with large woody fuel consumption (figure 8).

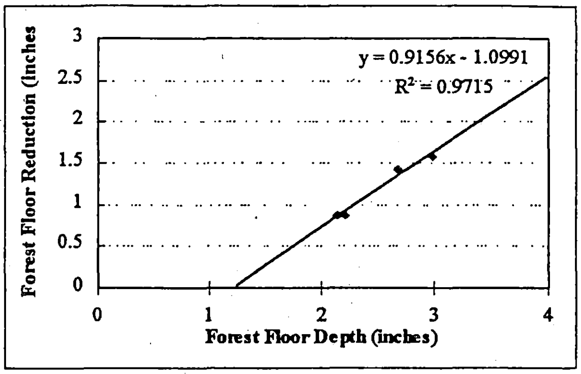

Figure 7. Forest floor reduction plotted against forest floor depth.

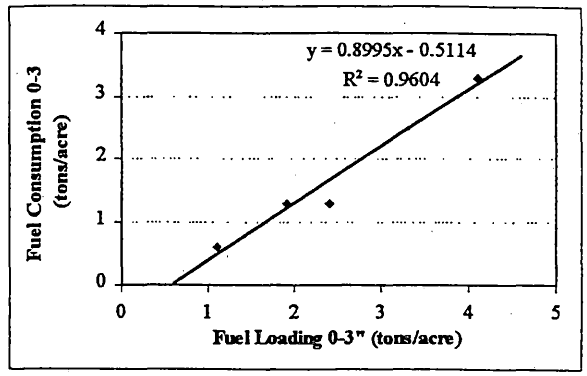

Figure 8. Fuel consumption plotted against fuel loading of the 0-3" diameter woody material.

Analysis and Discussion

The prescribed burns were completed under moderately wet conditions in mid-spring. The prescription called for dry enough conditions to consume a majority of the 0 to 0.25 and 0.25 to 1.0 inch diameter fuels and litter layer while retaining most large logs and 50 percent of the duff. These objectives were met. The burns were typical of the projected maintenance-type prescribed burning for forest health improvement in the Blue Mountain region of northeastern Oregon.

Fuel Consumption

The woody fuel and forest floor consumption was typical of a natural fuel site burned during the spring burning period. The consumption of the woody fuels and forest floor was not completely consistent with the predicted outputs from the fuel consumption model CONSUME (Ottmar and others 1993). CONSUME generally predicted the fuel consumption of the small and large woody fuels well but under-predicted the fuel consumption of the forest floor (figure 9). The First Order Fire Effects Model (FOFEM) (Keane and others 1994) predicted the small fuel

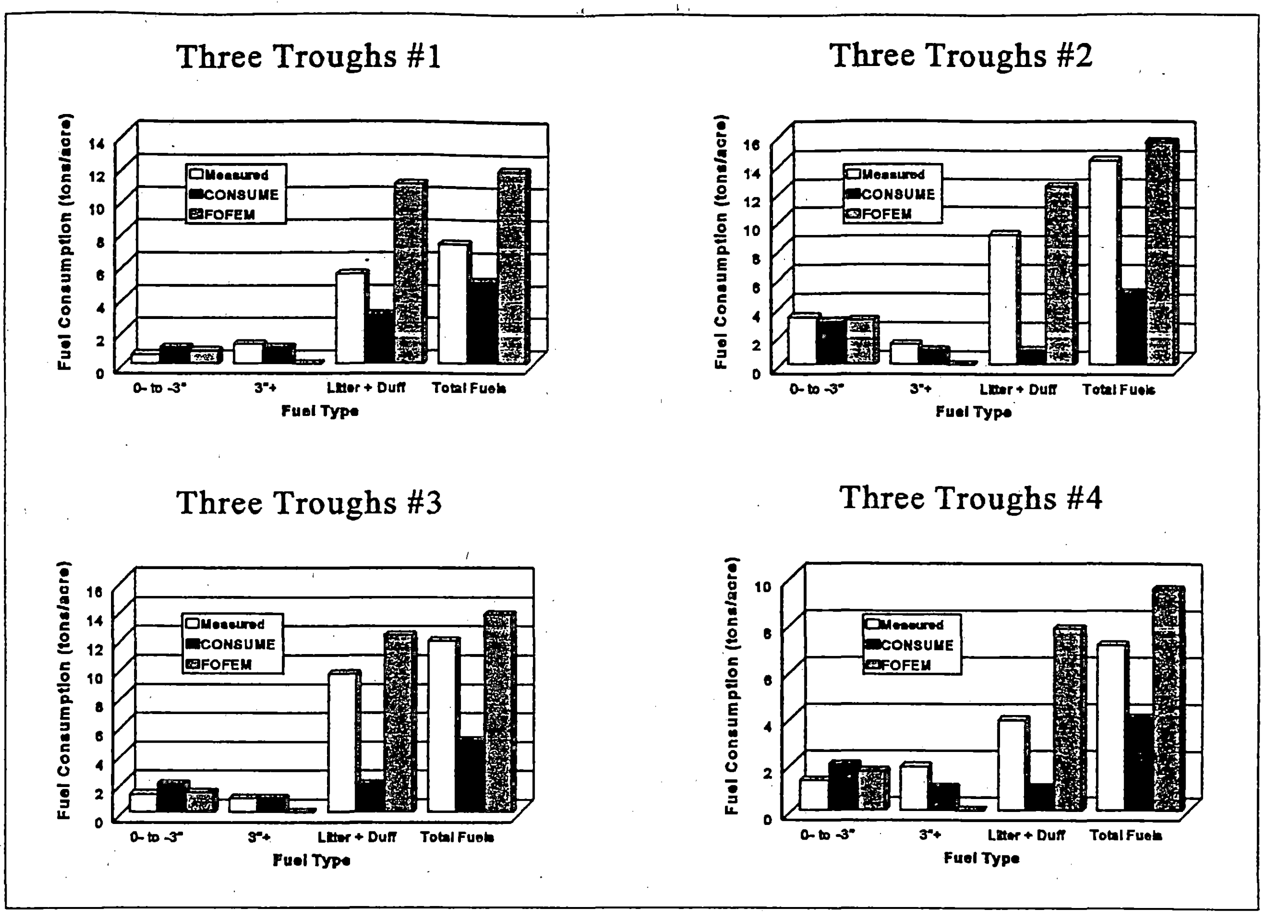

Figure 9. Measured fuel consumption compared with predicted fuel consumption from CONSUME and FOFEM.

consumption well but under-predicted the large woody fuel consumption and over-predicted the forest floor consumption.

Fuel consumption of the small fuels was predicted very well by CONSUME. CONSUME assumes that 80 to 90 percent of the small fuels consume during a prescribed burn. Past research (Ottmar and others 1990, Brown and others 1991) has supported this assumption. Fuel consumption of the small woody fuels, 0 to 3 inches in diameter is strongly correlated to the preburn fuel loading. This was evident with the Three Troughs data (tables 1 and 2). Generally, managers will not ignite a prescribed fire unless the small fuels are dry enough to carry the fire, 80 to 100 percent of the small fuels will be consumed, and their fuel reduction objectives will be met.

CONSUME predicted the large fuel consumption well for all the Three Trough units except #4. The adequate performance of CONSUME in predicting the large woody fuel consumption was

somewhat of a surprise. CONSUME was designed for clearcut sites in Oregon and Washington with a homogenous and continuous fuel bed of biomass debris created from logging. The fuels on the Three Troughs units were created from natural processes and the woody fuels were scattered and not continuous. This created areas of little or no fuels to carry the fire. Additionally, less small fuels were consumed than if there had been a continuous fuel bed. It was suspected that a discontinuous fuel bed would reduce fuel consumption as compared to a more homogenous fuel bed, causing CONSUME to over-predict the fuel consumption. This did not happen and indicates that the model may be more robust than previously thought. Fuel moisture content was shown to be the critical variable for the consumption of large woody fuels and is the main driver in CONSUME.

Although FOFEM predicted the consumption of the small fuels reasonably well, the model under-predicted the large woody fuel consumption and estimated there would be no consumption in this fuel size class (figure 9). The under-prediction could be due, in part, to the rotten nature of the larger fuel particles and the variability of the large fuels. FOFEM was designed for areas with uniform, homogenous, and continuous fuel beds and is expected to over-predict consumption in a natural fuel situation. In addition, the fuel consumption model used by FOFEM relies on preburn diameter, moisture content, and a seasonal adjustment to predict large woody fuel consumption. The preburn diameter is probably masking the influence of the fuel moisture which may be the critical variable controlling fuel consumption in natural fuels.

The forest floor loading carries the bulk of the fuels available for consumption. It is very important that these fuels are considered when estimating the total biomass consumed during a prescribed fire. Previous research has shown that forest floor consumption is related to preburn duff depth (Brown and others 1991), forest floor moisture content (Brown and others 1991), and large fuel consumption (Ottmar and others 1993). Comparing the forest floor consumption with predicted values from CONSUME, we can see that the predicted forest floor consumption was 1 to 4 times less than measured. CONSUME relates forest floor reduction to large fuel consumption, as determined from prescribed burns in logging slash. This same relationship may not exist in natural fuels.

FOFEM over-predicted the forest floor consumption in all cases by 20 to 100 percent. FOFEM relates the duff consumption to lower duff moisture content and preburn duff depth. At this point, it is unclear why the FOFEM equation performed poorly at these sites. For these models to be used in natural fuels, additional data sets and modification of the forest floor consumption equations are needed.

The inconsistency of CONSUME in predicting forest floor consumption in units with a natural fuel component was evident during the early 1990's. Consequently, a major research effort was initiated in 1992 to collect data on prescribed burns in natural fuels throughout the western United States. To date, over 30 units have been monitored in Oregon, Washington, and Arizona. These data are currently being analyzed and new fuel consumption equations are being developed for implementation in a new version of CONSUME scheduled for release in 1996. The equations will also be added to a new version of the Emissions Production Model, scheduled for release in 1997. The Three Troughs units are valuable additions to this data set.

Emissions of Trace Gases and Fine Particles

Emissions of CO_2, CO, CH_4, and several hydrocarbons were characterized by three FASS packages, each using a gas chromatograph (GC) equipped with a flame ionization detector (FID) for each of the 700 ml stainless steel canisters collected during the fires. The results are presented in Table 5 by phase of combustion for each of the three fires. Unadjusted, real time measurements of concentrations of CO_2 and CO were approximately 10 and 20% larger than the integrated samples of CO_2 and CO measured from the canister samples (figures 10 and 11), respectively. This may be a result of applying a single calibration to the CO_2 and CO analyzers rather than using the package-specific calibration algorithms. This possible calibration problem does not affect the calculation of emissions factors or the measurement of relative amounts of vegetation consumed by the flaming and smoldering phases. The overall precision was 96% for CO_2 and 99% for CO.

Table 5. Concentrations of CO_2, CO, CH_4, non-methane hydrocarbons (NMHC), and particles less than 2.5 μm diameter (PM2.5) for three prescribed underburns of eastern Oregon mixed-conifer forest type burned in May of 1994.

FIRE ID	CO_2 (ppm)	CO (ppm)	CH_4 (ppm)	C_2H_6 (ppm)	C_2H_4 (ppm)	C_2H_2 (ppm)	C_3H_6 (ppm)	C_3H_8 (ppm)	C_3H_4 (ppm)	NMHC (ppm)	PM2.5 (mg/m^3)
OR1_20_4F	591	25	2.40	0.11	0.34	0.10	0.10	0.02	0.02	0.77	4.75
OR1_20_4I	445	11	2.36	0.05	0.12	0.04	0.02			0.25	1.28
OR1_20_4S	502	17	2.78	0.09	0.18	0.05	0.07	0.03	0.02	0.49	3.04
OR1_22_4F	806	28	3.43	0.13	0.39	0.11	0.14	0.03	0.02	0.94	1.96
OR1_22_4I	686	31	4.72	0.25	0.46	0.11	0.17	0.05	0.02	1.21	4.01
OR1_22_4S	630	35	3.88	0.17	0.35	0.09	0.13	0.05	0.02	0.92	2.4
OR1_28_4F	480	9	2.29	0.05	0.16	0.06	0.05			0.37	2.39
OR1_28_4I	599	21	2.92	0.09	0.31	0.09	0.09	0.03	0.02	0.7	4.77
OR1_28_4S	593	25	3.24	0.11	0.35	0.11	0.11	0.03	0.02	0.82	5.64
OR2_20_4F	710	31	4.33	0.17	0.41	0.11	0.15	0.05	0.02	1.04	2.79
OR2_20_4I	884	65	7.32	0.36	0.70	0.16	0.27	0.09	0.03	1.85	8.99
OR2_20_4S	581	32	4.37	0.17	0.26	0.06	0.11	0.04	0.01	0.75	2.15
OR2_22_4F	515	12	2.60	0.07	0.16	0.05	0.04			0.36	1.96
OR2_22_4I	667	29	3.98	0.14	0.33	0.09	0.11	0.04	0.02	0.82	4.01
OR2_22_4S	681	35	4.45	0.17	0.38	0.11	0.13	0.04	0.02	0.96	5.89
OR2_28_4F	721	23	3.39	0.10	0.33	0.09	0.11	0.02	0.01	0.76	2.35
OR2_28_4I	613	35	4.64	0.19	0.34	0.08	0.15	0.05	0.02	0.96	5.34
OR2_28_4S	643	37	4.56	0.19	0.31	0.08	0.14	0.05	0.02	0.91	5.16
OR3_20_4F	533	23	3.43	0.12	0.23	0.09	0.10	0.04	0.03	0.68	4.26
OR3_20_4I	621	32	3.97	0.16	0.30	0.11	0.13	0.04	0.02	0.87	5.32
OR3_20_4S	594	33	3.82	0.17	0.35	0.10	0.12	0.04	0.02	0.9	5.49
OR3_22_4F	976	43	4.31	0.21	0.75	0.25	0.22	0.06	0.04	1.71	4.28
OR3_22_4I	874	50	5.34	0.26	0.69	0.19	0.23	0.05	0.03	1.65	11.09
OR3_22_4S	614	30	3.88	0.15	0.33	0.09	0.12	0.04	0.03	0.85	6.04
OR3_28_4F	605	17	2.82	0.07	0.29	0.10	0.08	0.02	0.02	0.64	2.9
OR3_28_4I	615	23	3.32	0.10	0.28	0.09	0.10	0.02	0.02	0.69	3.4
OR3_28_4S	464	15	2.90	0.10	0.15	0.05	0.06	0.03	0.01	0.45	2.28

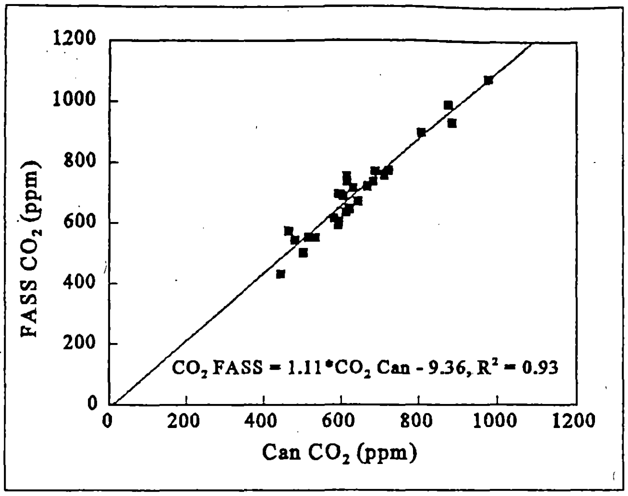

Figure 10. Comparison of integrated concentrations of CO_2 measured with FASS compared to CO_2 from integrated canister samples.

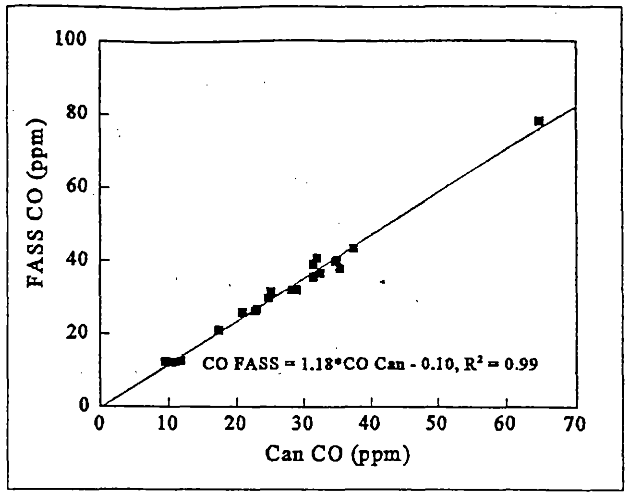

Figure 11. Comparison of integrated concentrations of CO measured with FASS compared to CO from integrated canister samples.

As noted previously, from samples collected at deforestation fires in Brazil, the slope coefficient for the concentration measured with the electro-chemical CO detector is not 1.0 because of the small response of the detector to hydrogen and oxygenated hydrocarbons.

PM2.5 concentrations ranged from 1.28 to 11.09 mg m^{-3} and are presented in Table 6 along with the sum of the individual hydrocarbons. The mass ratio of PM2.5 to CO is usually about 100 µg of PM2.5 per ppm of CO (Babbitt et al. 1995). Our ratio of PM2.5 to CO ranges from 58 to 326 µg PM2.5 per ppm of CO (table 6 and figure 12). The average of 158±52 µg PM2.5 per ppm CO is higher than expected, which suggests that particulate matter production is larger for natural fuels than most other fuel types studied.

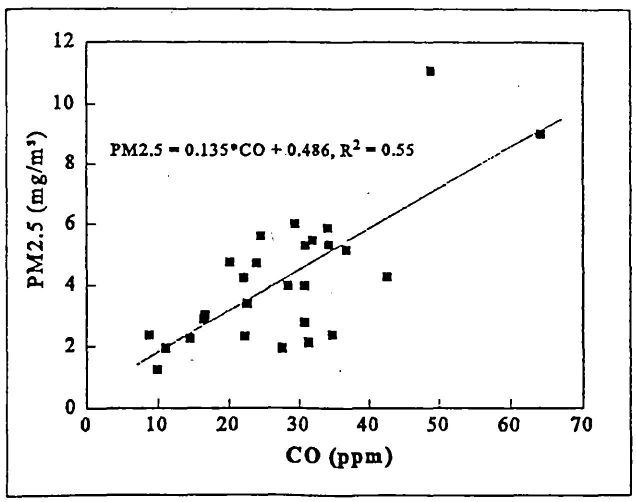

Figure 12. Correlation of particles less than 2.5 µm diameter (PM2.5) with the concentration of CO (ppm).

Combustion Efficiency

Combustion efficiency (CE) is defined as the ratio of carbon released in the form of CO_2 to the total carbon released. Values are presented in Table 7 by phase of combustion

and this ratio is used to evaluate the overall combustion conditions affecting the release of emissions. For the three fires, the average combustion efficiencies were 0.93, 0.89, and 0.86 for the flaming, intermediate, and smoldering phases of combustion, respectively. We use modified combustion efficiency (MCE) or the ratio of carbon released as CO_2 to the sum of carbon released as CO_2 and CO. This term is independent from other products of incomplete combustion but is highly correlated with CE (r = 0.98) as illustrated in Figure 13. Emission factors for products of incomplete combustion (CH_4, non-methane hydrocarbons (NMHC), and particulate matter) are negatively correlated with MCE and the products of incomplete combustion are generally intercorrelated (figures 14, 15, and 16).

Table 6. Net concentrations of CO_2, CO, CH_4, and nonmethane hydrocarbons after subtracting background concentrations from values found in Table 5 (data are for three prescribed underburns in a mixed-conifer type of eastern Oregon and took place in May of 1994).

FIRE ID	CO_2 (ppm)	CO (ppm)	CH_4 (ppm)	NMHC (ppm)	PM2.5 (mg/m^3)	PM2.5/CO (mass/mass)
OR1_20_4F	227	23.9	0.72	0.69	4.75	199
OR1_20_4I	81	9.8	0.68	0.23	1.28	131
OR1_20_4S	138	16.6	1.1	0.44	3.04	183
OR1_22_4F	442	27.5	1.75	0.82	1.96	71
OR1_22_4I	322	30.7	3.04	1.06	4.01	131
OR1_22_4S	266	34.7	2.2	0.81	2.4	69
OR1_28_4F	116	8.8	0.61	0.32	2.39	273
OR1_28_4I	235	20.1	1.24	0.63	4.77	237
OR1_28_4S	229	24.4	1.56	0.73	5.64	231
OR2_20_4F	346	30.7	2.65	0.91	2.79	91
OR2_20_4I	520	64.1	5.64	1.61	8.99	140
OR2_20_4S	217	31.3	2.69	0.65	2.15	69
OR2_22_4F	151	11.1	0.92	0.32	1.96	177
OR2_22_4I	303	28.3	2.3	0.73	4.01	142
OR2_22_4S	317	34.0	2.77	0.85	5.89	173
OR2_28_4F	357	22.2	1.71	0.66	2.35	106
OR2_28_4I	249	34.2	2.96	0.83	5.34	156
OR2_28_4S	279	36.7	2.88	0.79	5.16	141
OR3_20_4F	169	22.0	1.75	0.61	4.26	194
OR3_20_4I	257	30.8	2.29	0.76	5.32	173
OR3_20_4S	230	31.8	2.14	0.8	5.49	173
OR3_22_4F	612	42.5	2.63	1.53	4.28	101
OR3_22_4I	510	48.8	3.66	1.45	11.09	227
OR3_22_4S	250	29.3	2.2	0.76	6.04	206
OR3_28_4F	241	16.4	1.14	0.58	2.9	177
OR3_28_4I	251	22.5	1.64	0.61	3.4	151
OR3_28_4S	100	14.5	1.22	0.4	2.28	157

Table 7. Emission factors for CO_2, CO, CH_4, non-methane hydrocarbons (NMHC), and particles less than 2.5 µm diameter (PM2.5). Combustion efficiency (CE) and modified combustion efficiency (see text for definitions of CE and MCE) for each sample package by phase of combustion are also listed (data are for three prescribed underburns in a mixed-conifer type of eastern Oregon and took place in May of 1994).

FIRE ID	$EFCO_2$ (g/kg)	EFCO (g/kg)	$EFCH_4$ (g/kg)	EFNMHC (g/kg)	EFPM2.5 (g/kg)	CE (ratio)	MCE (ratio)
OR1_20_4F	1607	108	1.9	3.6	18.7	0.876	0.905
OR1_20_4I	1588	122	4.8	3.1	14.0	0.866	0.892
OR1_20_4S	1577	121	4.6	3.8	19.3	0.860	0.893
OR1_22_4F	1704	67	2.5	2.4	4.2	0.929	0.941
OR1_22_4I	1626	99	5.6	4.0	11.3	0.887	0.913
OR1_22_4S	1585	132	4.8	3.6	8.0	0.864	0.885
OR1_28_4F	1649	79	3.2	3.3	18.9	0.899	0.930
OR1_28_4I	1635	89	3.1	3.2	18.5	0.891	0.921
OR1_28_4S	1593	108	3.9	3.8	21.9	0.869	0.904
OR2_20_4F	1648	93	4.6	3.2	7.4	0.899	0.919
OR2_20_4I	1577	124	6.2	3.7	15.2	0.860	0.890
OR2_20_4S	1560	143	7.0	3.5	8.6	0.850	0.874
OR2_22_4F	1667	78	3.7	2.5	12.0	0.909	0.932
OR2_22_4I	1633	97	4.5	2.9	12.0	0.891	0.915
OR2_22_4S	1602	109	5.1	3.2	16.6	0.873	0.903
OR2_28_4F	1699	67	3.0	2.3	6.2	0.926	0.941
OR2_28_4I	1550	135	6.7	3.9	18.5	0.845	0.879
OR2_28_4S	1566	131	5.9	3.3	16.1	0.854	0.884
OR3_20_4F	1554	129	5.9	4.3	21.8	0.847	0.885
OR3_20_4I	1579	120	5.1	3.5	18.2	0.861	0.893
OR3_20_4S	1548	136	5.2	4.0	20.6	0.844	0.879
OR3_22_4F	1685	74	2.6	3.1	17.0	0.919	0.935
OR3_22_4I	1614	98	4.2	3.4	7.5	0.880	0.913
OR3_22_4S	1577	118	5.0	3.6	21.2	0.860	0.895
OR3_28_4F	1678	73	2.9	3.0	11.2	0.915	0.936
OR3_28_4I	1640	93	3.9	3.0	12.4	0.894	0.918
OR3_28_4S	1535	142	6.8	4.6	19.5	0.837	0.873

Fuel Consumed by Flaming and Smoldering Combustion

Concentrations of CO_2 and CO were multiplied by the vertical vector and used to calculate the relative carbon released by phase of combustion. We combined the carbon release during the intermediate and smoldering phases into one value for the smoldering phase. There may have been some flaming combustion during the intermediate phase which could have contributed to the low fuel consumption of 33%, as compared to nearly 50% as suggested through the use of methods for predicting fuel consumption by phase of combustion. For grassland fires (Ward et al. 1995), the fuel consumption would be typically near 100% for the flaming phase of combustion and 50% for logging slash (Ward and Hardy 1991). The ratios of flaming and smoldering combustion to total fuel consumed for the three fires were very consistent (figure 17) with a relative standard deviation of approximately 25% for the flaming phase and less than 15% for the smoldering phase.

Emission Factors of CO_2, CO, CH_4, Other Hydrocarbons, and PM2.5

Emission factors were calculated using a carbon mass balance method (Ward and Hardy, 1991). Emission factors averaged 1654±13, 85±5, 3.5±0.32, 3.1±0.31, and 13.1±3.38 g kg^{-1} of fuel for the flaming phase of combustion and 1571±13, 127±5, 5.4±.68, 3.7±0.29, 16.9±2.7 g kg^{-1} for the smoldering phase of combustion for CO_2, CO, CH_4, NMHC, and PM2.5, respectively. The emission factors for the intermediate combustion phase suggest a mixture of flaming and smoldering combustion. The individual emission factors for CH_4 are inversely correlated with MCE (figure 18). Emission factors for NMHC can be predicted from those for CH_4 (figure 19).

Weighted emission factors combine the measurements by phase of combustion, based on the amount of carbon released during each phase of combustion. Individual weighted emission factors for CH_4, NMHC, and PM2.5 for each of the 9 observations of the three fires are presented in Figures 20 to 22. The weighted average emission factors for the three burns are 1617±38, 104±18, 4.4±1, 3.3±0.4, and 14.2±4.8 g kg^{-1} for CO_2, CO, CH_4, NMHC, and PM2.5, respectively (table 8). The emission factors for CO, CH_4, NMHC, and PM2.5 are comparable to those of logging slash fires in the Pacific Northwest (Ward and Hardy, 1991).

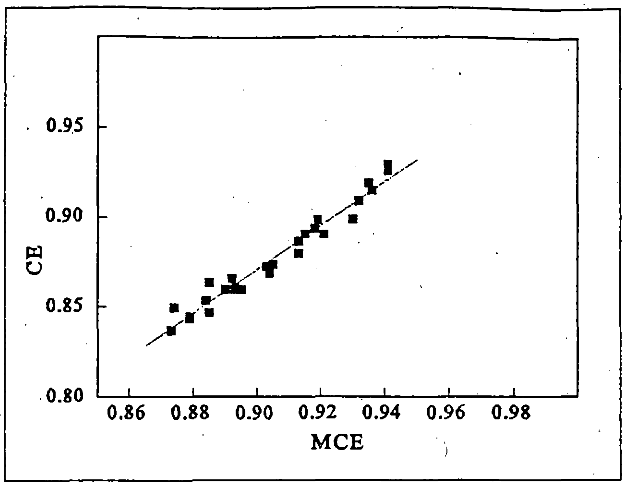

Figure 13. Correlation of combustion efficiency (CE) with the ratio of CO_2 to the sum of CO_2 and CO (MCE).

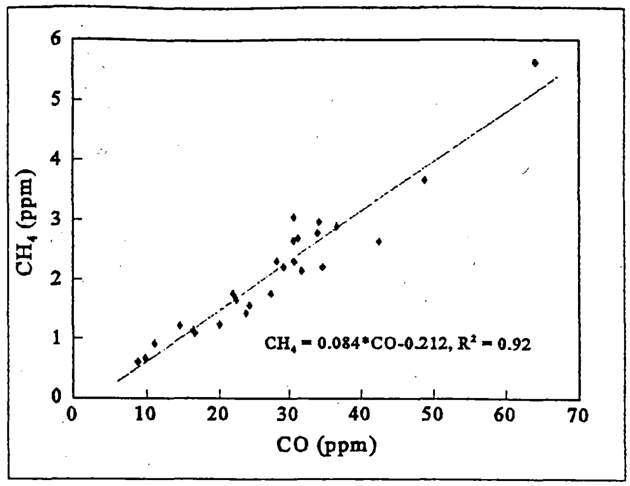

Figure 14. Comparison of concentrations of CH_4 to CO for the Oregon underburn study.

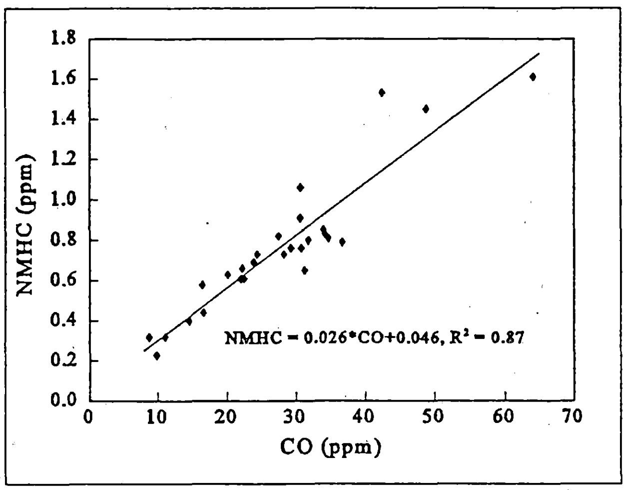

Figure 15. Comparison of concentrations of non-methane hydrocarbons (NMHC) to CO for the Oregon underburn study.

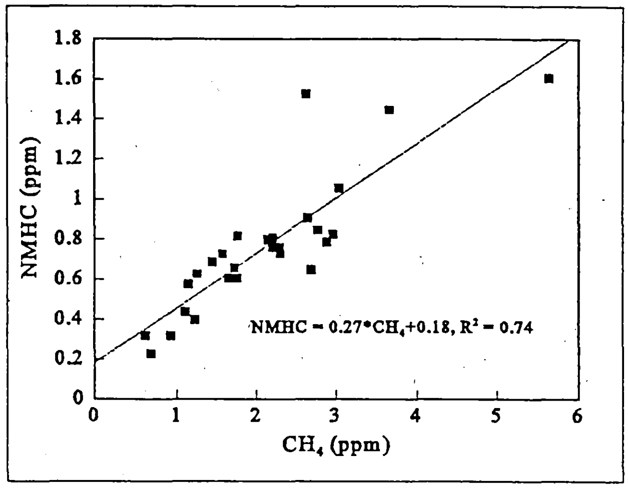

Figure 16. Comparison of concentrations of non-methane hydrocarbons to CH_4 for the Oregon underburn study.

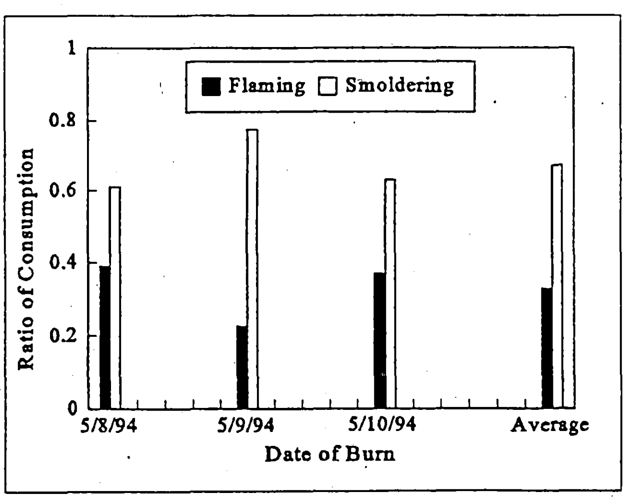

Figure 17. Fuel consumption by phase of combustion for the Oregon underburn study (flaming phase average: 37%).

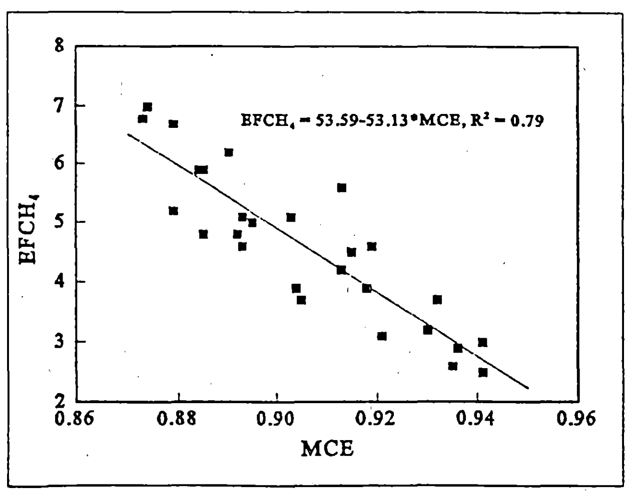

Figure 18. Comparison of emission factors for CH_4 with the ratio of CO_2 to the sum of CO_2 and CO (MCE).

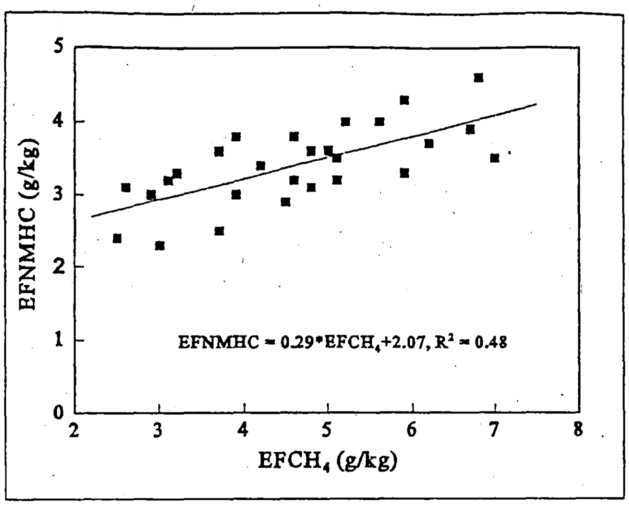

Figure 19. Comparison of emission factorsof non-methane hydrocarbons (EFNMHC) with emission factors for methane ($EFCH_4$).

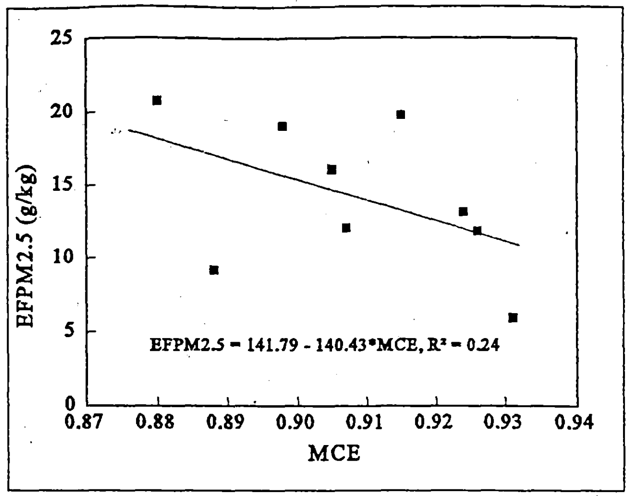

Figure 20. Emission factors for particles less than 2.5 μm diameter correlated with the ratio of CO_2 to the sum of CO_2 and CO (MCE).

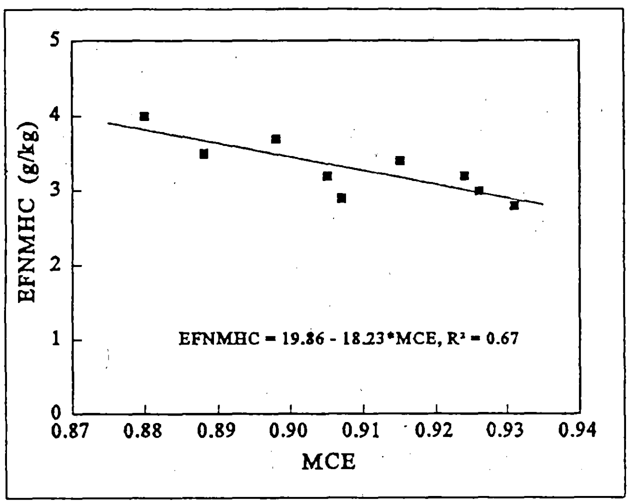

Figure 21. Weighted average emission factors for non-methane hydrocarbons correlated with the ratio of CO_2 to the sum of CO_2 and CO (MCE).

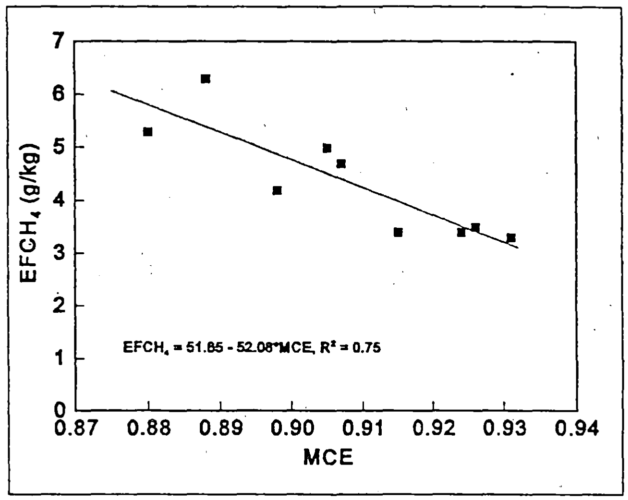

Figure 22. Weighted average emission factors for CH_4 with ratio of CO_2 to the sum of CO2 and CO.

Table 8. Weighted emission factors for CO_2, CO, CH_4, NMHC, PM2.5, CE, and MCE for each of three underburns conducted in eastern Oregon during May of 1994 in mixed-conifer stands. See text for definitions and explanation of method used for computing weighted values.

FIRE ID	$EFCO_2$ (g/kg)	EFCO (g/kg)	$EFCH_4$ (g/kg)	EFNMHC (g/kg)	EFPM2.5 (g/kg)	CE (ratio)	MCE (ratio)
OR1_20_4W	1589	115	3.5	3.7	19.1	0.867	0.898
OR1_22_4W	1678	79	3.3	2.8	6.0	0.915	0.931
OR1_28_4W	1620	96	3.4	3.4	19.8	0.883	0.915
OR2_20_4W	1585	128	6.3	3.5	9.2	0.864	0.888
OR2_22_4W	1605	108	5.0	3.2	16.1	0.875	0.905
OR2_28_4W	1620	105	4.7	2.9	12.1	0.884	0.907
OR3_20_4W	1549	135	5.3	4.0	20.8	0.844	0.880
OR3_22_4W	1651	86	3.4	3.2	13.2	0.900	0.924
OR3_28_4W	1656	85	3.5	3.0	11.9	0.903	0.926
Average	**1617**	**104**	**4.3**	**3.3**	**14.2**	**0.882**	**0.908**

When the weighted average combustion efficiency of 0.882 in Ward and Hardy's (1991) equations is used, calculated emission factors are 93.1, 4.6, 3.6, and 8.5 g kg^{-1}, respectively, for CO, CH_4, NMHC, and PM2.5. The values are -10, +0.5, +8, and -67% of those measured for the underburning experiments, suggesting that the emissions of smoke particles may be underestimated by previous models of Ward and Hardy (1991).

Conclusions

Fuel loading and fuel consumption were measured on 4 prescribed burned areas with natural fuels in the Blue Mountains of northeastern Oregon. Emissions were characterized on three of these burn areas.

The fuel consumption was typical of a moderately wet spring burn. CONSUME adequately predicted the fuel consumption of the small and large fuels, but under-predicted the fuel consumption of the forest floor. The internal equations of CONSUME were designed from data collected at clearcut prescribed fires and will need to be further tested and possibly modified to better represent the combustion process for natural fuels. FOFEM predicted the fuel consumption of the small fuels well but substantially under-predicted the consumption of the larger fuels and over-predicted the consumption of the forest floor.

The emission factors for CO, CH_4, NMHC, and PM2.5 for the eatern Oregon underburns are comparable to those of logging slash fires in the Pacific Northwest (Ward and Hardy, 1991). When the weighted average combustion efficiency of 0.882 in Ward and Hardy's (1991) equations is used, calculated emission factors are 93.1, 4.6, 3.6, and 8.5 g kg^{-1}, respectively, for CO, CH_4, NMHC, and PM2.5. The values are -10, +0.5, +8, and -67% of those measured for the underburning experiments, suggesting that the emissions of smoke particles may be underestimated by previous models of Ward and Hardy (1991).

These data from the Three Troughs units are being added to a much larger data set composed of prescribed fire fuel consumption information collected from ponderosa pine and mixed conifer natural fuel burns across the western states. This database is currently being used to modify the fuel consumption models for implementation into a new version of CONSUME, scheduled for release in 1996. The equations will also be added to a new version of the Emissions Production Model, scheduled for release in 1997. The Three Troughs units are valuable additions to this data set.

Recommendations

To develop management strategies for the reintroduction of fire into the landscape, land managers and decision makers will need a model that estimates fuel consumption, heat, and emissions for new prescribed burning situations in natural fuels. Prescribed fires in natural fuels are ignited slowly. This, in combination with a limited amount of fuel, reduces the probability of a dynamic plume development. A major effort to collect data for this type of burning and to modify current fuel consumption and source strength models is currently underway, supported by USDA Forest Service Regions 3 and 6 and the Department of the Interior. With an additional, small investment, more comprehensive smoldering data could be collected to improve the late smoldering stage source strength model. This decade marks the last major push in field experiments and it may be a long time before we have another opportunity to blend modeling requirements with field techniques.

References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press. 493p.

Beaufait, W.R.; Hardy, C.E.; Fisher, W.C. 1977. Broadcast burning in larch-fir clearcuts: Miller Creek-Newman Ridge study. Res. Pap. INT-175. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Brown, James K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station; 24 p.

Brown, James K.; Reinhardt, Elizabeth D.; Fischer, William C. 1991. Predicting duff and woody fuel consumption in northern Idaho prescribed fires. Forest Science, Vol. 37, No. 6, pp. 1550-1566.

Brown, James K.; Michael A Marsden; Kevin C. Ryan;, and Elizabeth D. Reinhardt. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. Research Paper INT-337. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 23 p.

Huff, Mark H.; Ottmar, Roger D.; Alvarado, Ernesto; Vihnanek, Robert E.; Lehmkuhl, John F.; Hessberg, Paul F.; and Everett, Rich L. 1995. Historical and current forest landscapes in eastern Oregon and Washington. Part II: linking vegetation characteristics to potential fire behavior and related smoke production.. Gen. Tech. Rep. PNW-GTR-335. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 43p.

Keene, Robert E.; Reinhardt, Elizabeth D.; Brown, James K. 1994. FOFEM: A first order fire effects model for predicting the immediate consequences of wildland fire in the United States. In: Proceedings 12th Conference on Fire and Forest Meteorology; 1993 October 26-29; Jekyll Island, GA. Boston, MA: American Meteorological Society: pp. 628-631.

Little, Susan N.; Ottmar, Roger D.; Ohmann, Janet L. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. Res. Pap. PNW-362. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 29 p.

Martin, R. E. and others. 1979. Effects of fire on fuels: A state-of-knowledge review. Gen. Tech. Rep. WO-13. Washington D.C. U.S. Department of Agriculture, Forest Service. 64 p.

Mutch, R.W.; Arno, S.F.; Brown, J.K.; Carlson, C.E.; Ottmar, R.D.; Peterson, J.L. 1993. Forest health in the Blue Mountains: A fire management strategy for fire-adapted ecosystems. Gen. Tech. Rep. PNW-310. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 14 p.

Norum, Rodney A. 1977. Preliminary guidelines for prescribed burning under standing timber in western larch/Douglas-fir forests. Research Note INT-229. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 15 p.

NWCG 1985. Prescribed fire smoke management guide produced by: fire and fire effects working team. NFES No. 1279. U.S. Department of Interior, Boise Interagency Fire Center, Boise, ID. 28 p.

Ottmar, Roger D. 1983. Predicting fuel consumption by fire stages to reduce smoke from slash fires. In: 1983 annual meeting proceedings, Northwest Fire Council; 1983 November 21-22; 1983; Olympia, WA. Olympia, WA: Northwest Fire Council; 1984: pp. 87-106.

NWCG 1985. Prescribed fire smoke management guide produced by: fire and fire effects working team. NFES No. 1279. U.S. Department of Interior, Boise Interagency Fire Center, Boise, ID. 28 p.

Ottmar, Roger D. 1983. Predicting fuel consumption by fire stages to reduce smoke from slash fires. In: 1983 annual meeting proceedings, Northwest Fire Council; 1983 November 21-22; 1983; Olympia, WA. Olympia, WA: Northwest Fire Council; 1984: pp. 87-106.

Ottmar, Roger D.; Hall, Janet N.; and Vihnanek, Robert E. 1990. Improved preiction of fuel consumption during spring-like prescribed burns. Unpublished final report, ODIN Corporation contract 89-617. 56 p. On file with USDA Forest Service, Pacific Nborthwest Research Station, Seattle, WA.

Ottmar, Roger D.; Burns, Mary F., Hall, Janet N. 1993. CONSUME Users Guide. Gen. Tech. Rep. PNW-GTR-304. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 118 p.

Sandberg, David V. 1980. Duff reduction by prescribed underburning in Douglas-fir. Res. Pap. PNW-272. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 18 p.

Sandberg, D.V.; Peterson, J.L. 1985. A source strength model for prescribed fires in coniferous logging slash. In: Proceedings, 21st annual meeting of Air Pollution Control Association, Pacific Northwest International Section; 1984, November 12-14; Portland, OR: Air Pollution Control Association; 1985. 10 p.

Southern Forestry Science Laboratory. 1976. Southern forestry smoke management guidebook. Gen. Tech. Rep. SE-10. Macon GA: U.S. Department of Agriculture, Forest Service, Southeastern Forest and Range Experiment Station. 140 p.

U.S. Forest Products Laboratory. 1974. Wood handbook: wood as an engineering material. Agric. Handb. 72, rev. Washington D.C.: U.S. Department of Agriculture.

Ward, Darold E.; Peterson, Janice L.; Hao, Wei Min. 1994. An inventory of particulate matter and air toxic emissions from prescribed fires in the USA for 1989. EPA Final Report IAG-DW12934736-01-0-1989. 19 p.

Ward, Darold E.; Hardy, Colin C. 1991. Smoke emissions from wildland fires. *Environment International*, Vol. *17*, pp. 117-134.